TR 203

Technical Report 203

AD 717239

SETTLING CHARACTERISTICS OF ACTIVATED SLUDGE AT LOW TEMPERATURE

Sherwood Reed

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CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
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PREFACE

Authority for the investigation reported herein is contained in FY1966, *Instructions and Outline, Military Construction Investigations, Engineering Criteria and Investigations and Studies, Investigation of Arctic Construction; Utilities in Permafrost Areas.*

At the time of this investigation the Military Construction Investigations (MCI) program was conducted for the Engineering Division, Directorate of Military Construction, Office, Chief of Engineers, and was administered by the Civil Engineering Branch. The MCI program is currently conducted for the Office of Plans, Research and Systems (OPRS), Directorate of Military Construction, Office, Chief of Engineers. This study was performed by Mr. Sherwood C. Reed, Research Civil Engineer, Construction Engineering Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL).

This report was also submitted as a thesis in partial fulfillment of the requirements for the M.S. degree in Environmental Health Engineering under the direction of Dr. R. Sage Murphy, University of Alaska. The author wishes to acknowledge the guidance and encouragement offered by Dr. Murphy during the course of this work, and to recognize the contribution made by the staff at the USA CRREL Alaska Field Station. The operational support provided by Mr. Robert Bell was particularly valuable.

The investigations were performed under the general supervision of Mr. K.A. Linell, Chief, Experimental Engineering Division, USA CRREL, and the direct supervision of Mr. E.F. Lobacz, Chief, Construction Engineering Branch, USA CRREL.

LTC J.F. Castro was Commanding Officer/Director of USA CRREL at the time of publication of this report.

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by

Sherwood C. Reed

INTRODUCTION

Sewage treatment was generally considered unnecessary or impossible for arctic and subarctic communities until recently. When a clear need was defined, standard practice was to encapsulate the entire treatment system to maintain a Temperate Zone environment. This avoidance of temperature problems was purchased with a very costly and continuing investment in thermal energy. Current research is directed toward systems that can function with minimum thermal input. Work has generally concentrated on aerobic systems because higher operating temperatures are an accepted biological requirement for efficient anaerobic processes. Studies on an aerated lagoon (Reid, 1966; Pohl, 1967) and other variations of the activated sludge process (Reed, 1966; Murphy and Grube, 1967) in Alaska seem to indicate that the aerobic systems can operate with little or no applied thermal protection. However, most of the research to date has concerned the biokinetics of these systems. To provide maximum efficiency in the total operation, the solids-liquid separation phase of these processes must receive comparable attention.

Clarification is one of the basic processes of all sewage treatment and some measure to obtain it are included in every type of treatment system. These may range from simple pon.. elaborate tanks with complex hydraulic and mechanical elements. All generally depend on t.. gravity settling of solid particles through the liquid media. The term "gravity settlement" masks a very complex .ay of interacting parameters so that, in spite of considerable investigation, the process for activated sludge is only partially understood. The function of temperature in the sedimentation of sewage sludges is not well defined and conflicting interpretations are found in the literature. This parameter has increased significance for the design of systems in low temperature areas of the world and it is therefore the primary subject of this investigation.

THEORETICAL CONSIDERATIONS

Sludge characteristics

Prior to a discussion of the settling process it is necessary to consider the nature and source of the particulate matter involved. The solids concentration in a domestic waste entering an activated sludge unit is usually small compared with the concentration of solids carried in the system. It can therefore be said that most of the solids in an aeration unit are produced by the in-situ biological activity. This factor is responsible for the wide variability in the settling performance of sewage sludges since any operational change that affects the biokinetics in the system may in turn directly or indirectly influence the settling.

Although domestic sewage is remarkably similar in character throughout the United States, it has not been possible to develop an analytical design technique that can be generally applied. In each case, it is necessary to develop the required design parameters from a preliminary series of laboratory investigations. The situation becomes even more complex when the waste contains a variety of industrial products.

The activated sludge particle as described by Eckenfelder and O'Connor (1961) is "a miscellaneous collection of microorganisms such as bacteria, yeasts, molds, protozoa, rotifers, worms and insect larvae in a gelatinous mass." The character of the microbial population in this floc strongly influences settling behavior but is obviously a result of the biokinetics in the system and therefore subject to other operational parameters. Temperature can be a significant factor in the metabolic processes involved and could have an indirect influence on settling from this source.

In any solid-liquid gravity separation system, the desired optimum conditions are large, heavy, effectively flocculent particles. Definition of these features in terms of size, shape, density and surface characteristics may quite often be possible in industrial processes and some water and sewage applications (i.e. grit removal). Definition of activated sludge floc in these terms is, for the reasons stated above, impossible for practical purposes.

Although a quantitative description of an ideal sludge particle is not feasible, it is informative to consider its general developmental process and the influence of temperature on it.

Physical adsorption of colloidal and suspended matter is a well recognized capability of activated sludge. It is the factor responsible for the rapid initial removal of 5-day biochemical oxygen demand (BOD_5) in contact stabilization and similar processes. It can be shown by the Gibbs equation that the amount of adsorption at a surface is a function of the system temperature:

$$\Gamma = -\frac{C}{RT}\frac{\gamma_2 - \gamma_1}{C_2 - C_1} \tag{1}$$

where:

Γ = amount adsorbed at concentration C
C = concentration of the solute in the solution
C_1, C_2 = any two solute concentrations near C
γ = surface tension of the solution
γ_1, γ_2 = surface tension of the solution at concentrations C_1 and C_2
T = absolute temperature
R = universal gas constant.

Since the rate of adsorption is inversely proportional to temperature, it should be more rapid at lower temperatures than at high temperatures. At low temperatures, this might tend to produce larger and heavier particles containing an increased proportion of stored nutrient material since the metabolic activity should be decreased. These larger and heavier particles would tend to compensate for increased fluid viscosity, resulting in a larger than expected settling velocity at the lower temperatures. Some evidence of nutrient storage might be found in a sludge that demonstrates an increasing volatile content as the temperature is decreased. Increased volatility could also be interpreted as an increase in the number of active organisms present. As the metabolic rate lowers with lowering temperature, the extra nutrients are available to support an increased population. Temporary nutrient storage would depend on temperature limitations of metabolic and reproductive activities while providing for physical adsorption of the excess nutrients in the biological floc. This concept would produce an equilibrium condition physically similar to the effects of an increase in microbial population. Present techniques used to evaluate system performance and efficiency could be used to justify either possibility. Some improved technique to identify the active microbial fraction in the sludge will be required for absolute definition.

Flocculation and adsorption are essentially similar phenomena, at least in their influence on settleability. Flocculation is usually described as the collision of particles and the resulting agglomeration into larger units. Adsorption as described above is usually discussed in terms of surface phenomena, the net effect being the production of larger particles.

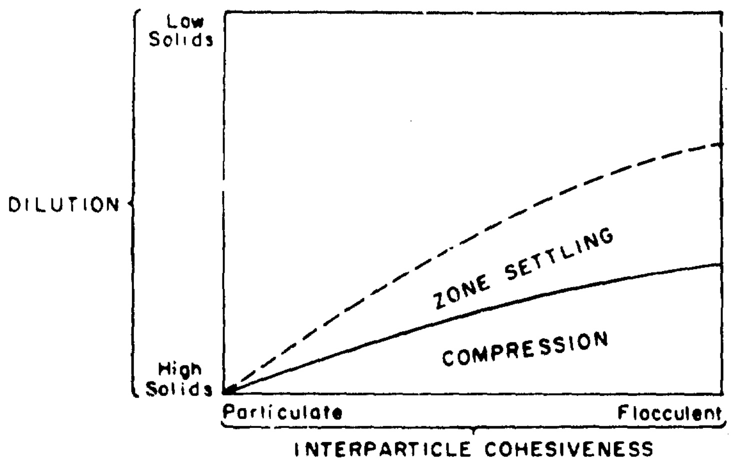
According to accepted theory, the number of interparticle contacts and possible aggregation in a settling flocculent suspension is inversely proportional to viscosity (Fair and Gyer, 1954). An adverse effect on flocculation and therefore particle size and settling velocity might be expected at low temperatures. Hawks (Pohl, 1967) suggested that the biological flocculation of sludge particles follows a process similar to the electrokinetic theory of chemical coagulation. This coagulation theory indicates that the process can be promoted by a contraction of the diffuse double layer. Since, as shown by Mackrle (1962), the effective thickness of this layer is directly dependent on the square root of absolute temperature, the possibility for enhanced coagulation exists at lower temperatures. In addition, most of the organic particles found in sewage are hydrophilic and may be surrounded by a solvated envelope. As the system temperature is lowered it seems possible that migration of water molecules from this envelope to the solvent might occur, leading to increased coagulation potential.

All of the factors discussed up to this point would tend, either singly or in concert, to enhance sludge floc development at low temperatures. A force in the opposite direction is the temperature-dependent viscosity parameter which would retard the movement and therefore the contact and growth of particles in a quiescent system. In the aeration chamber of the activated sludge system, where the coagulation-flocculation-growth operations are occurring, the fluid viscosity can be neglected for practical purposes. The turbulence in the system, required for the desired complete mixing, will negate any viscosity influence on interparticle movement and contacts. This should permit the full advantages of enchanced adsorption and coagulation to occur at the lower temperatures. The resulting floc should be larger and heavier than its high temperature counterpart and, at least initially, should contain a higher proportion of unoxidized organic nutrients. Thomas (1950) observed "...particles in sewage tend to be somewhat larger and heavier in cold weather." This should be valid for activated sludge as well as raw sewage for, in the latter case, the solubility of the organic fractions will be reduced at lower temperatures and any turbulence in the pipe systems will enhance aggregation.

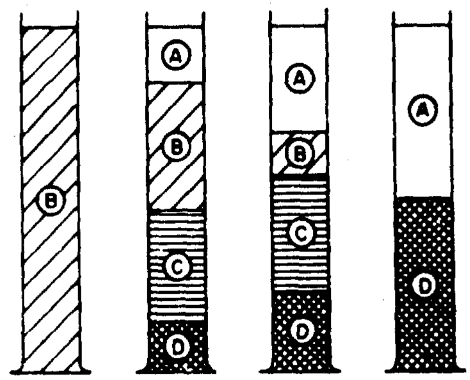
Settling theories

Particles will settle out of a suspension in one of four basic ways, depending on concentration and flocculating properties as described by classical theory (Fitch *et al.*, 1958). The paragenesis diagram shown in Figure 1a illustrates the relationship between these factors. The settlement of activated sludge is usually assigned to the zone settling portion of this diagram (Eckenfelder and O'Connor, 1961; Fitch *et al.*, 1958; Rich, 1961).

The classic description of zone settling and related calculation techniques for basin design were presented by Coe and Clevenger (1916). Figure 1b illustrates this process. Starting with an initial uniform concentration zone *B*, settlement proceeds through the formation of a transition zone C and a compression zone *D*. The concentration of particles in zone *B* remains constant so the zone settles at a uniform velocity until the transition zone is approached. In zone *D* the particles are mechanically supported by the solids below and settling in this area is analogous to the con-



a. *Paragenesis diagram.*



b. Zone settling. The interface between A and B moves down at a constant velocity. This uniform rate is by definition the zone settling velocity.

Figure 1. Paragenesis diagram and zone settling.

solidation of soils. Zone *A* represents the clarified supernatant. The constant rate movement of zone *B* is by definition the zone settling velocity of the material.

Apparently Coe and Clevenger (1916) did not recognize the importance of temperature until field tests at operational plants were attempted. They noted that higher temperatures seemed to produce more effective settlement and suggested a safety factor be employed in basin design "... to take care of changes in character of pulp and variations in temperature."

The starting point for defining particle settling velocity is usually Newton's law describing frictional drag (Eckenfelder and O'Connor, 1961):

$$F_D = \frac{C_D \; A \; V_s^2 \; \rho_L}{2g} \tag{2}$$

where:

F_D = drag force
A = projected area of particle
C_D = drag coefficient
ρ_L = fluid density
V_s = settling velocity of particle.

The drag coefficient has been shown to be a function of the Reynolds number, which relates frictional and inertial forces in the system (Eckenfelder and O'Connor, 1961):

$$N_{Re} = \frac{V_s \, D}{\mu} \tag{3}$$

where:

N_{Re} = Reynolds number
D = particle diameter
μ = absolute viscosity of fluid.

A variety of expressions relating the drag coefficient and the Reynolds number for different conditions have been developed. The most familiar assumes low velocity, laminar flow, $C_D = 24/N_{Re}$; this leads to Stokes' law:

$$V_s = \frac{1}{18} \frac{(\rho_s - \rho_L) g D^2}{\mu} \tag{4}$$

where:

ρ_s = particle density, and other terms are as defined previously.

Although theoretically limited to the unhindered low velocity settlement of small diameter spherical particles in an infinitely deep medium, eq 4 is widely applied. The settling velocity indicated by this expression is stongly temperature dependent through the viscosity paramerer. Figure 2 illustrates this relationship for a particle of typical size and weight. Although sewage sludge does not satisfy many of the Stokes' law prerequisites, Schropfer (Thomas, 1950) and Fischerström (1967) noted the same inverse velocity-viscosity relationship when studying performance of actual tanks. However, there is no general agreement on this point. Thomas (1950) cited studies by Ridenour and by Jenkins *et al*, which did not show any significant temperature effects.

At the concentrations normally considered in activated sludge treatment, the settling process is normally considered hindered because of interparticle interferences and nonlaminar flow of fluid in the system. Under these conditions the zone settling sequence described previously becomes the basic mechanism. In batch settling tests a distinct solid/liquid interface appears initially and settles at a uniform rate until the transition zone is encountered. The theoretical analysis of these phenomena by Kynch (1952) is based on the assumption that the settling velocity at a particular point in the suspension is dependent only on the local concentration. This indicates that the initial suspension concentration at the interface remains unchanged until it encounters a layer of higher concentration propagated up from the bottom of the vessel. From this point on, the settling velocity will continually decrease until the compression stage is reached.

The work of Talmage and Fitch (1955), based on the Kynch theory, provides a simple graphical technique for the analysis of settling curves to produce the parameters required for basin design. This approach, summarized in Figure 3, is included in all current textbooks and has gained wide acceptance as a design technique.

The recent evaluation of these settling theories by Dick and Ewing (1967) concludes that the Kynch theory and related techniques are valid for ideal suspensions, but the settling behavior of activated sludge does not conform to the ideal model. They found that the zone settling velocity for activated sludge depended on the depth of the suspension in addition to the expected concentration dependence. Dick and Ewing suggested the presence of interparticle forces as the factor responsible for retarded activated sludge zone settling. This implies that some fraction of the weight of sludge particles at the top of the suspension is transmitted through the structure to the bottom of the suspension. Dick and Ewing showed experimentally that as the depth increased its

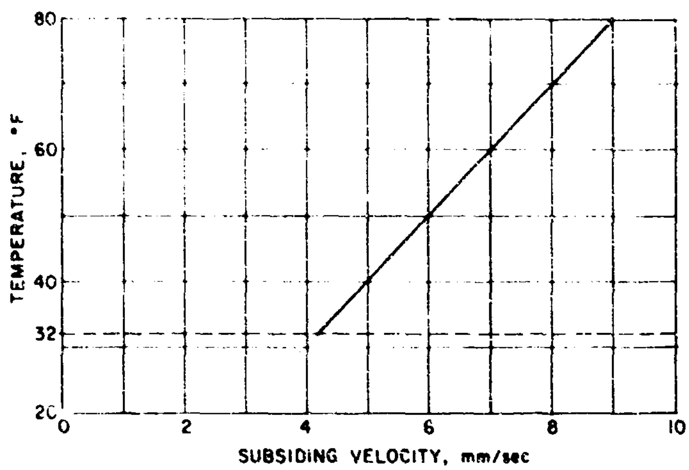
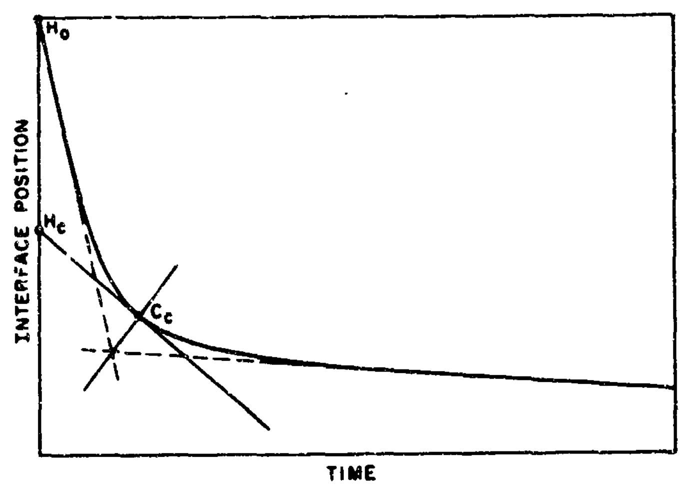


Figure 2. Settling velocity vs temperature, Stokes' law, 0.5-mm particle, 1.2 specific gravity. (After Alter, 1969).



1. Observe settlement of initial suspension C_0 starting from initial height H_0.
2. Construct tangent to initial portion of curve; slope of this line is V_s, zone settling velocity.
3. Construct tangent to compression part of curve.
4. Bisect angle formed by two tangents; mark intersection of bisector with curve; this is point where compression starts.
5. Construct tangent through C_c; determine value of H_c from ordinate.
6. Since $C_0H_0 = C_cH_c$, it is possible to solve for C_c. Knowing C_c and V_s it is possible to compute unit area required for clarification and thickening. The largest required area controls design.

Figure 3. Analysis of zone settling curve according to technique of Talmage and Fitch (1955).

influence decreased, and mixing, resulting in the destruction of the sludge structure at the bottom, increased settling velocity. Both of these factors tend to support their theo' regarding sludge structure.

Dick and Ewing did not discuss temperature effects in their analysis, nor are there any significant references in most of the standard textbooks or available design references. It is assumed that the cold regions designer would fall back on the familiar velocity-viscosity-temperature relationships as expressed by Stokes' law by applying a comparable factor to zone settling design.

In a recent article Tesařík (1967) discussed sludge-blanket clarifiers, primarily as used in water treatment and softening applications. He cited an equation developed by Allen and rearranged terms in a combined form to produce an expression for the escape velocity of water leaving the sludge blanket. Tesařík showed that if particle sizes and specific gravities are assumed to be invariant with temperature velocity is proportional to the cube root of the kinematic viscosity:

$$\frac{V_1}{V_2} = \left(\frac{\nu_2}{\nu_1}\right)^{1/3} \tag{5}$$

where:

V_1, V_2 = upflow velocity at T_1 and T_2
ν_1, ν_2 = kinematic viscosity at T_1 and T_2.

If:

$$T_1 = 0°C \text{ and } T_2 = 20°C$$

then:

$$\frac{V_1}{V_2} = 0.825. \tag{6}$$

This is significantly different from the value predicted by a similar application of Stokes' law:

$$\frac{V_1}{V_2} = \frac{\mu_2}{\mu_1} = 0.563. \tag{7}$$

These two values are believed to represent the limiting temperature conditions and it is apparent that an incorrect choice could have considerable significance in the design of a particular system. It was therefore the major purpose of this study to investigate the temperature parameter in terms of activated sludge and to produce additional information that might be of assistance in developing a better understanding of the fundamental sedimentation process.

METHOD OF TESTING

A small extended aeration activated sludge plant located at the CRREL Alaska Field Station, Fairbanks, Alaska, was used for this study. This prefabricated unit was designed for a 2000-gal/day flow at a volumetric loading of 15 lb/day of 5-day biochemical oxygen demand (BOD_5) per 1000 cu ft of aeration capacity. The two-compartment unit included a 2000-gal aeration tank and a 672-gal settling tank providing a hydraulic retention time at design flow of 24 and 8 hours, respectively. A submerged diffused air system provided the necessary aeration and mixing in the primary tank and an airlift pump returned settled sludge from the settling tank to the aeration tank. During this study the time-switch-controlled aeration system was operated on a 15-min/hr schedule and, since the airlift pump operation was a concurrent function, sludge was returned at the same schedule. The sludge return flow rate was maintained at approximately 10 gal/min. This was a very high rate for the size of the unit but was adopted to avoid possible freezing problems in the sludge piping.

The unit was operated at a level significantly below design capabilities with an average inflow of 850 gal/day during the study period. To attain even this level some supplementation was required since the normal domestic waste flow averaged only 250 gal/day. The supplement consisted of approximately 600 gal/day of water added uniformly to the system with a measured amount of dried dog meal to maintain the same proportional level of organic material in the total flow. This required approximately 4.8 lb/day of dried material and produced an organic loading on the unit of 0.03 lb of BOD_5/day per pound of Mixed Liquor Volatile Suspended Solids (MLVSS) during the sampling periods discussed here. Dog meal has been used successfully in previous studies (Ludzack *et al.*, 1961; Ludzack, 1965; Murphy and Nesbitt, 1964) as a feed supplement. Its application to this full-scale system was apparently successful since the operational characteristics observed in the unit were comparable to similar systems receiving only domestic wastes.

The treatment unit was housed in an insulated building equipped with a thermostatically controlled heating and ventilating system. This permitted very close environmental control over the building interior and treatment unit contents. Since the primary interest for this and related concurrent studies centered on low temperatures, the fluids in the treatment system were maintained at 10°C or less for most of the 180-day study period. During the latter part of February the unit was maintained with a fluid temperature slightly in excess of 1°C.

The high sludge return rate, coupled with the low operational temperatures, produced a predictably high solids concentration in the system. The Mixed Liquor Suspended Solids (MLSS) increased from 4700 mg/l on 2 October to 12,600 mg/l on 12 February. During this period the volatile fraction showed a gradual increase from 80 to 90%. Sludge was wasted on 19 February, restoring the solids concentration to approximately the original value. Most of the sampling for the test program described here was done at a MLSS of 5000-6000 mg/l either before or after the sludge waste period.

Standard 1-liter graduated cylinders were used as the settling tubes by Standard Methods (American Public Health Association (APHA), 1965) for the activated sludge settleability test. The lack of stirring and the possibility of wall effects, depth effects and diameter effects described by other investigators were all recognized as potentially detrimental influences. However, since this investigation was originally intended as a pilot study to detect gross temperature effects on settling more sophisticated equipment was not believed to be warranted.

Samples were obtained directly from the aeration tank during the aeration cycle to ensure a completely mixed representative condition. Portions of the original samples were retained at the original concentration. Two other dilutions were then prepared using volumetric techniques. Clarified plant effluent was used as the diluting water in all cases. If, as Dick and Ewing (1967) suggested, a structure exists in the settling mixture, the nature of the fluid in the system might in some way contribute to stability; and, since temperature effects were the major point of interest, any viscosity change induced by dilution with another fluid would tend to confuse results. The use of a diluting fluid similar to the liquid present in the original sample was adopted to minimize these unknown and possibly adverse effects. The three samples were then mixed well and decanted simultaneously into separate 1-liter graduated cylinders. The sludge/liquid interface in the three cylinders was observed at 1-min intervals and recorded.

Most of the tests were terminated when the data indicated the onset of compression in the settling samples. The environmental control system in the building assured constant temperature conditions during the test run. Following the first run, a second set of fresh samples was obtained in an identical manner and transferred to an adjacent warm building. These bottled samples were immersed in a warm water bath for a sufficient period to raise the samples to room temperature. This usually required 10-15 min. The samples were then allowed to stand for 15 min to ensure a stable temperature. Samples were re-mixed, decanted and observed as described. A series of six such tests would then produce settling data on three different concentrations at two temperatures.

On two occasions, three temperature levels were used. At these times, at the completion of the low temperature run, two sets of samples were prepared. One was left at the treatment unit and the environmental controls were set at the intermediate temperature, while the third set was transferred to the warm building for the high temperature run. This usually required 1-1½ hours and proved sufficient to raise the sample and the surrounding environment to the desired level for the intermediate run.

In each case a portion of the original sample was reserved for a determination of suspended solids. Gooch crucibles and the technique described in Standard Methods (APHA, 1965) were used except that glass fiber filter pads were used in place of the prescribed asbestos slurry. The concentration of the dilutions was calculated using the volumetric dilution data.

As a check on cylinder performance, several tests were run to compare directly settling in the cylinder and in the aeration tank. For this purpose a graduated rod was suspended in the aeration tank. The aeration equipment was then turned off simultaneously with decanting the smaller sample and the interface position in the small cylinder and tank was observed.

TEST RESULTS

Thirty individual temperature controlled tests were made. At low concentrations it was difficult to identify the sludge/liquid interface until nearly all of the particles had settled and compression had started. For this particular sludge the lower limiting concentration for the appearance of a distinct interface and obvious zone settling was from 2000-3000 mg/l. Below 2000 mg/l downward particle movement appeared to be completely unhindered and the entire settling process was over in a few minutes. Even at 2000 mg/l the interface was indistinct, and a sharp demarcation was not apparent until just prior to the onset of compression. Since the definition of the settling performance to this point was of major interest, the four tests performed at concentrations of less than 2000 mg/l are not included in this analysis. For the same reason, most of the tests were terminated after 35-40 min when compression was clearly occurring. Of the 26 tests reported only 6 were run for a maximum of 60 min. Figure 4 illustrates typical results from these long-term tests.

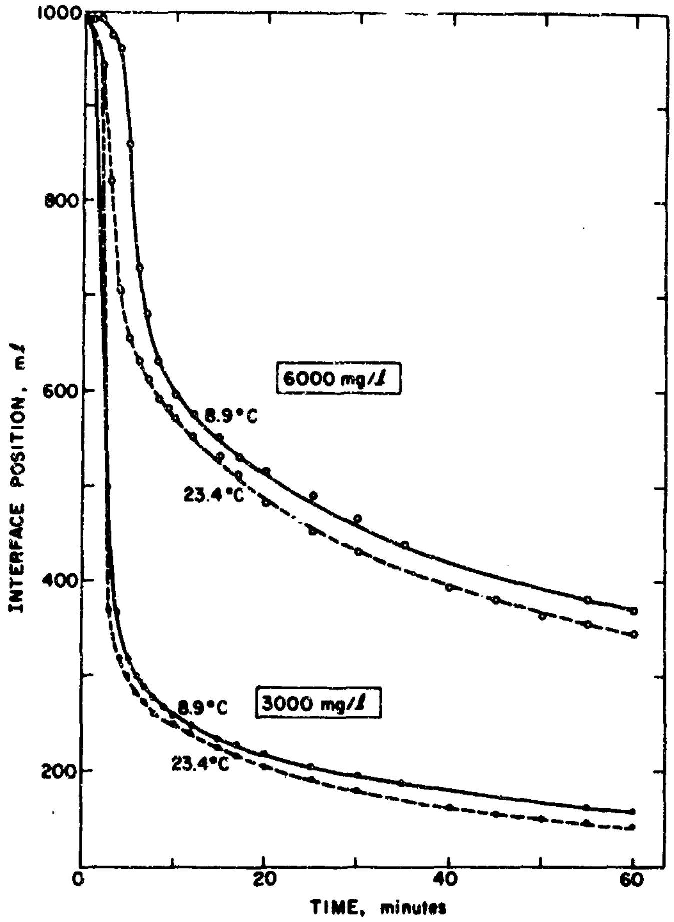


Figure 4. Typical settlement vs time data, 2 March 1958. (100 ml = 4.13 - cm depth)

Typical results from one of the three temperature series are shown in Figures 5-7. The plots are purposely limited to the first 10 min of each test to permit an enlarged scale that clearly demonstrates the linearity in the zone settlinr portion of the curve. The influence on zone settling because of concentration and temperature is clearly apparent when these figures are compared.

Similar plots were made for each test and the zone settling velocity was determined. In most cases, particu..arly at the higher concentrations, there was an initial lag prior to the onset of true settling (see Fig. 5). In these cases the velocity was determined from the portion of the curve representing obvious zone ttling (the essentially linear portion following the time lag, but prior to the onset of compression). Each graduated cylinder was carefully measured so that the interface position could be converted from the milliliter graduations to a linear distance. The resulting velocity values were expressed in meters per hour to permit direct comparison with other published values. These velocities and other pertinent test data are summarized in Table I.

Results of a special comparison between settlement in a 1-liter cylinder and the quiescent aeration tank are shown in Figure 8. An initial lag was observed in both cases. The onset of compression was observed in the cylinder but lack of adequate illumination forced termination of observations after 30 min in the prototype tank. In both of the tests shown the settling velocity in the tank was approximately 20% higl er than that observed in the test cylinder. Comparison with data of Dick

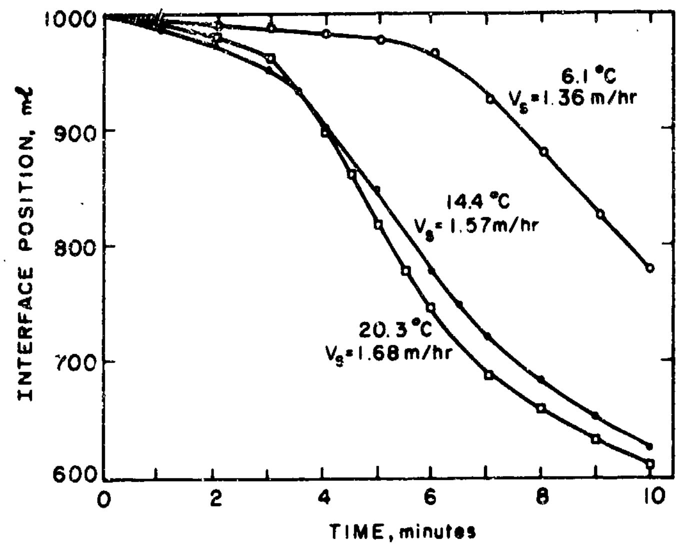


Figure 5. Interface settling curves, 6000 mg/l, 10 March 1968. (100 ml = 4.13 – cm depth)

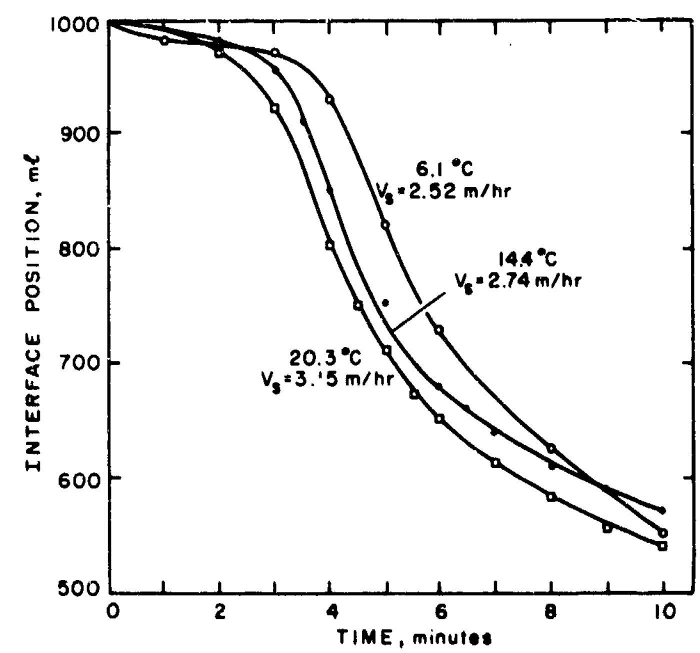


Figure 6. Interface settling curves, 5340 mg/l, 10 March 1968. (100 ml = 4.13 – cm depth)

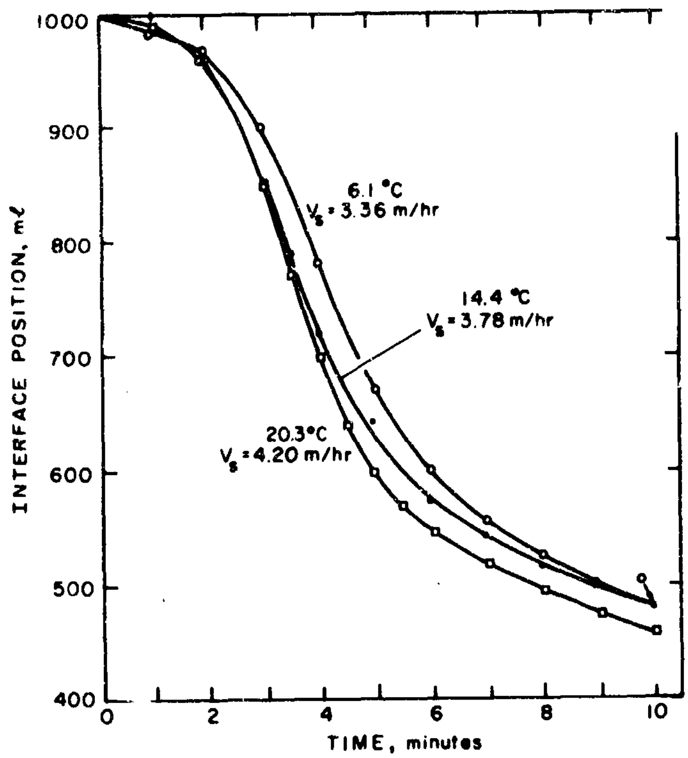


Figure 7. Interface settling curves, 4670 mg/l, 10 March 1968. (100 ml = 4.13 – cm depth)

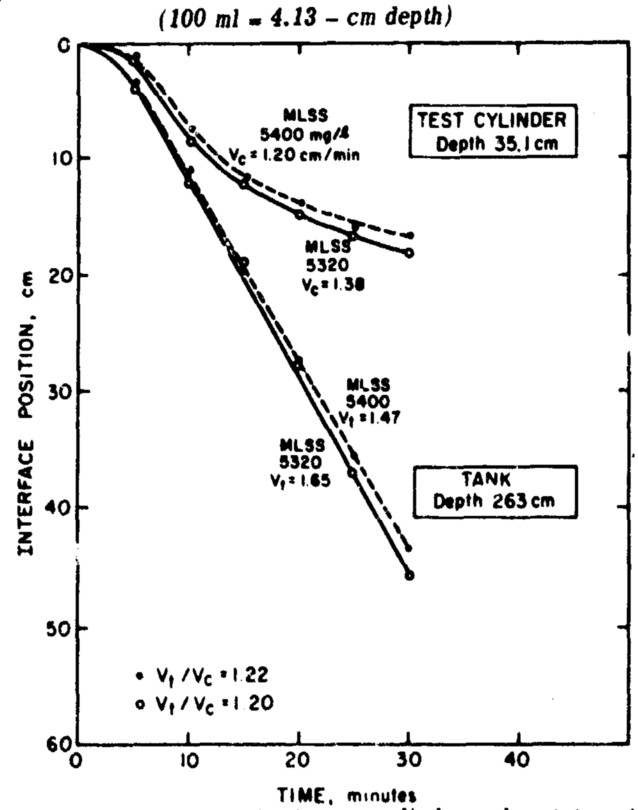


Figure 8. Settling behavior in test cylinder and prototype tank. V_t tank velocity; V_c cylinder velocity.

Table I. Test results.

Initial concentration (mg/l)	Temperature (°C)	Zone settling velocity (m/hr)	30-min settleability (ml)	Sludge * volume index	Test date
6000	21.1	1.47	440	73	20 Dec 1967
	7.2	1.26	470	78	20 Dec 1967
	23.4	2.52	430	72	2 Mar 1968
	8.9	1.26	465	77	2 Mar 1968
	20.3	1.68	410	68	10 Mar 1968
	14.4	1.57	440	73	10 Mar 1968
	6.1	1.36	515	86	10 Mar 1968
6467	20.0	1.79	460	71	9 Mar 1968
	13.6	1.68	480	74	9 Mar 1968
	7.2	1.26	650	100	9 Mar 1968
5340	20.3	3.15	360	68	10 Mar 1968
	14.4	2.74	400	75	10 Mar 1968
	6.1	2.52	400	75	10 Mar 1968
5000	17.8	3.48	410	82	21 Feb 1968
	1.1	2.63	380	76	21 Feb 1968
4670	20.3	4.20	310	66	10 Mar 1968
	14.4	3.78	330	71	10 Mar 1968
	6.1	3.20	340	73	10 Mar 1968
3000	23.4	6.51	180	60	2 Mar 1968
	8.9	4.42	195	65	2 Mar 1968
	17.8	5.67	180	60	21 Feb 1968
	1.1	3.38	210	70	21 Feb 1968
2000	23.4	7.35	110	55	2 Mar 1968
	8.9	4.90	125	62	2 Mar 1968
	17.8	6.30	125	62	21 Feb 1968
	1.1	3.68	140	70	21 Feb 1968

$* = \dfrac{(\text{30-min settleability}) \times 1000}{C_0}$ (from APHA, 1965).

and Ewing (1967) for approximately the same concentration and depth ratio indicated the same magnitude of variation. In their study other factors were constant and the 20% variation was attributed to the influence of depth. A comparable assignment in this study of the entire 20% variation to depth influence would indicate that other factors (wall effects, etc.) were minor.

As stated previously, only six tests were continued for 60 min. Results from the transition and compression portions of these tests are summarized on Table II. The critical concentration values C_c, defined by Talmage and Fitch (1955) as the concentrations at which compression starts, were determined by their graphical procedure (Fig. 3).

Table II. Transition and compression test data.

Initial concentration (mg/l)	*Temperature (°C)*	*Critical concentration* C_c* *(mg/l)*	*Compression velocity* V_c† *(m/hr)*	*Test date*
6000	23.4	9380	0.042	2 Mar 1968
6000	8.9	9400	0.042	2 Mar 1968
3000	23.4	9830	0.021	2 Mar 1968
3000	8.9	9100	0.021	2 Mar 1968
2000	23.4	8900	0.021	2 Mar 1968
2000	8.9	8300	0.021	2 Mar 1968

* Determined using graphical technique of Talmage and Fitch (1955) summarized in Figure 3.

† Determined as slope of compression segment of interface settling curves.

DISCUSSION

Qualitative comparisons

The settling tests, as shown in Table I, were performed from 1.1°C to 23.4°C; this should, therefore, include most operational fluid temperatures that might be considered for cold sewage treatment systems.

The zone settling velocities from 23 of the 26 tests are plotted versus temperature in Figure 9. In each case the values for a particular concentration can be fitted with a straight line. At least three points were available except for the 5000 mg/l data. A straight line through the two points in this case was felt to be justified. There is only one point showing significant divergence from others in a set and that is 6000 mg/l at the 23.4°C temperature. No explanation can be determined since the lower concentration dilutions tested the day of these tests show excellent correlation.

Values from Figure 9, at three representative temperatures (1°, 10°, 20°C), are plotted on Figure 10. The effects of concentration and temperature are apparent. The temperature effects obviously diminish with increasing concentration. As shown, it is possible to extrapolate smoothly the three curves through a common point on the abscissa (6667 mg/l). These curves would seem to indicate that there is an upper limiting concentration beyond which zone settling will not occur and an ultimate temperature-dependent settling velocity at very low concentration. This is not meant to imply that no settling occurs above the higher concentration (6667 mg/l in this case), but rather that the second mechanism, transition settling, occurs. In the transition zone the concentration and velocity are by definition constantly changing so true zone settling cannot occur.

An initial review of the literature for comparative data at first yielded contrary findings. Many of the standard textbooks (Eckenfelder and O'Connor, 1961; Fair and Geyer, 1954; Rich, 1961) present typical data which demonstrate a curvature opposite to that shown on Figure 10 with a tendency to become asymptotic on both the ordinate and abscissa. These presentations are believed to be unrealistic, since even at the lowest concentration (a single particle) there should be a

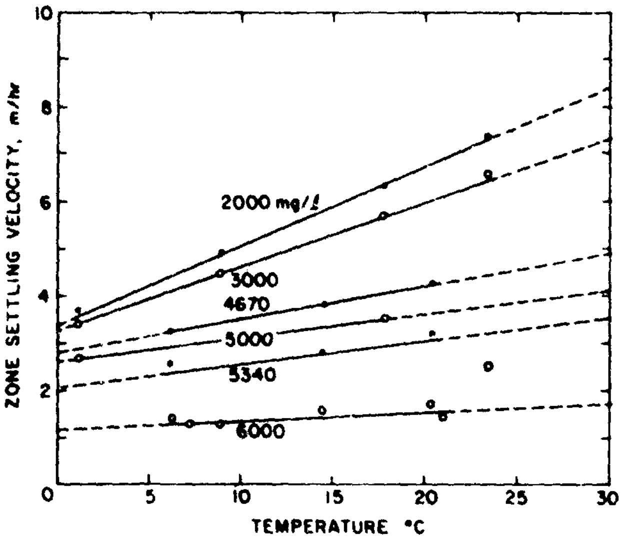


Figure 9. Zone settling velocity vs temperature.

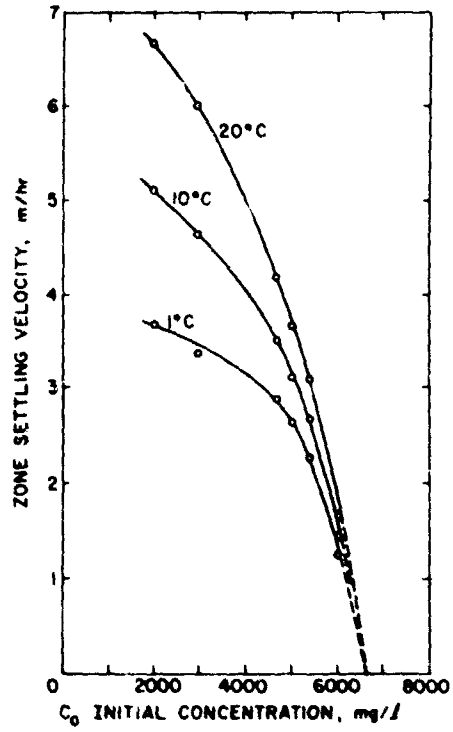


Figure 10. Zone settling velocity vs concentration (data interpolated from Fig. 9).

maximum limiting velocity as described by Stokes' law. The asymptotic appearance at the high concentrations is believed due to an attempt to describe the entire settling mechanism from onset through compression with a single concept. A plot of interface position versus time (similar to plots of Fig. 5-7) at a very high concentration will be essentially similar to the transition and compression portions of the curve for the same material tested at a lower concentration. In the latter case a continuous velocity change is recognized in the transition stage; therefore, a tangent to the curve in the former case does not really represent zone settling but transitional settling velocity at that point in time. Thus, a plot of these high concentration velocities, as an extension of lower concentration data, which truly exhibits zone settling, would tend to show the asymptotic behavior illustrated in the textbooks.

The data reported by Dick and Ewing (1967) were based on sludge from three separate plants. Values were extracted from their plots of velocity versus depth for a depth equivalent to the 1-liter cylinders used in this study. These are summarized in Table III. If plotted, they show dissimilar curvature, but all have a tendency toward a definite intercept on both the abscissa and ordinate; this lends support to the similar indications of this study. The differing curvature is believed significant and is tentatively suggested to be a function of a particular sludge type as influenced by some combination of the biochemical and operational parameters discussed in *Theoretical Considerations* (p. 1). This point is further illustrated by an examination of Fischerström's (1967) results. He reports zone settling velocities and concentrations from 17 different activated sludge plants in Sweden. The reason no correlation was possible is believed due to the differing sludge characteristics from the units examined. Unfortunately, a maximum of only two values was reported from a single plant, so no analytical treatment of Fischerström's data is possible. The lack of conformity in settling performance, as illustrated by the comparisons above, demonstrates why there can be no ideal curve and why a separate analysis is needed for each case.

Table III. Summary of data extracted from Dick and Ewing (1967).

Organic loading	Sludge volume index	Initial concentration (C_0) (mg/l)	Zone settling velocity (V_s) (m/hr)
	Plant A		
$\frac{0.14 \text{ lb } BOD_5/\text{day}}{\text{lb MLVSS}}$	75	3175	2.98
		4415	2.02
		5440	1.34
		5910	0.98
		6435	0.635
		6535	0.439
	Plant B		
$\frac{0.06 \text{ lb } BOD_5/\text{day}}{\text{lb MLVSS}}$	55	4310	3.54
		4615	3.20
		5020	2.82
		6185	1.71
		6785	1.24
		7735	0.525
	Plant C		
$\frac{1.35 \text{ lb } BOD_5/\text{day}}{\text{lb MLVSS}}$	300	1110	3.02
		1325	1.73
		1730	1.13
		1850	0.550
		2070	0.353

In general, the settling velocities obtained in this study fall in the range reported for activated sludge (Eckenfelder and O'Connor, 1961), with a tendency to be somewhat higher at any given concentration. This may be due to operational characteristics since the treatment unit was run at a very low organic loading, long retention time (2.36 days) and high solids age. Another factor might be the substrate character, since dried dog food was used as a supplement. However, operational results seem to indicate that this supplement was not essentially different from normal domestic waste components. The influent 5-day biological oxygen demand (BOD_5), chemical oxygen demand (COD) and suspended solids, both total and volatile, were comparable with those of another activated sludge unit under study in the Fairbanks area (Grube and Murphy, 1969).

The operational characteristics of the treatment unit conform to accepted theories describing extended aeration biokinetics; it is therefore assumed that the dog food had no adverse effects and that the sludge studied had the general characteristics of a normal activated sludge. An alternate explanation for higher settling velocity is enhanced particle size and weight due to the temperature factors discussed in *Theoretical Considerations*. A future test series will be necessary to evaluate this point. The unit will be allowed to come to equilibrium during the summer months with all other factors held constant. Test procedures, identical to those described here, will be performed with the sludge produced at high temperatures and cooled prior to testing to give the same temperature ranges presented here. The short-term temperature change should affect only the properties of the liquid fraction. If this second series shows significantly lower settling velocities than reported here, this would be supporting evidence for the development of larger, heavier particles at the lower temperatures.

Quantitative analysis

Quantitative analysis of the temperature and concentration relationships indicated in Figure 10 becomes possible if the values are replotted as V_s versus C, as shown in Figure 11a for a typical set. In this form

V_s = zone settling velocity (m/hr)

$$C = \frac{1000}{C_0} - \frac{1000}{C_{max}} \tag{8}$$

where:

C_0 = initial suspension concentration mg/l

C_{max} = maximum concentration of a sludge for true zone settling = 6667 mg/l for this study.

A value of 1000 was adopted as the numerator in eq 8 for arithmetic simplicity. As shown in Figure 11b the above takes the functional form

$$\frac{C}{V_s} = A + KC. \tag{9}$$

Rearrangement of terms yields:

$$V_s = \frac{C}{A + KC}. \tag{10}$$

For the 20° C data, functionally plotted on Figures 11a and 11b, the value A = 0.008 and K = 0.124. Similar analysis of data (from Fig. 9) at other representative temperatures produced the values listed in Table IV. It is seen that the value A is constant and invariant with temperature. The factor K is temperature dependent and, as shown on Figure 12, capable of definition with the exponential form:

$$\frac{K_T}{K_{20^\circ C}} = \theta^{(T - 20^\circ)} \tag{11}$$

where

K_T = factor at temperature T

K_{20} = factor at 20° C

θ = 0.968

T = temperature, °C.

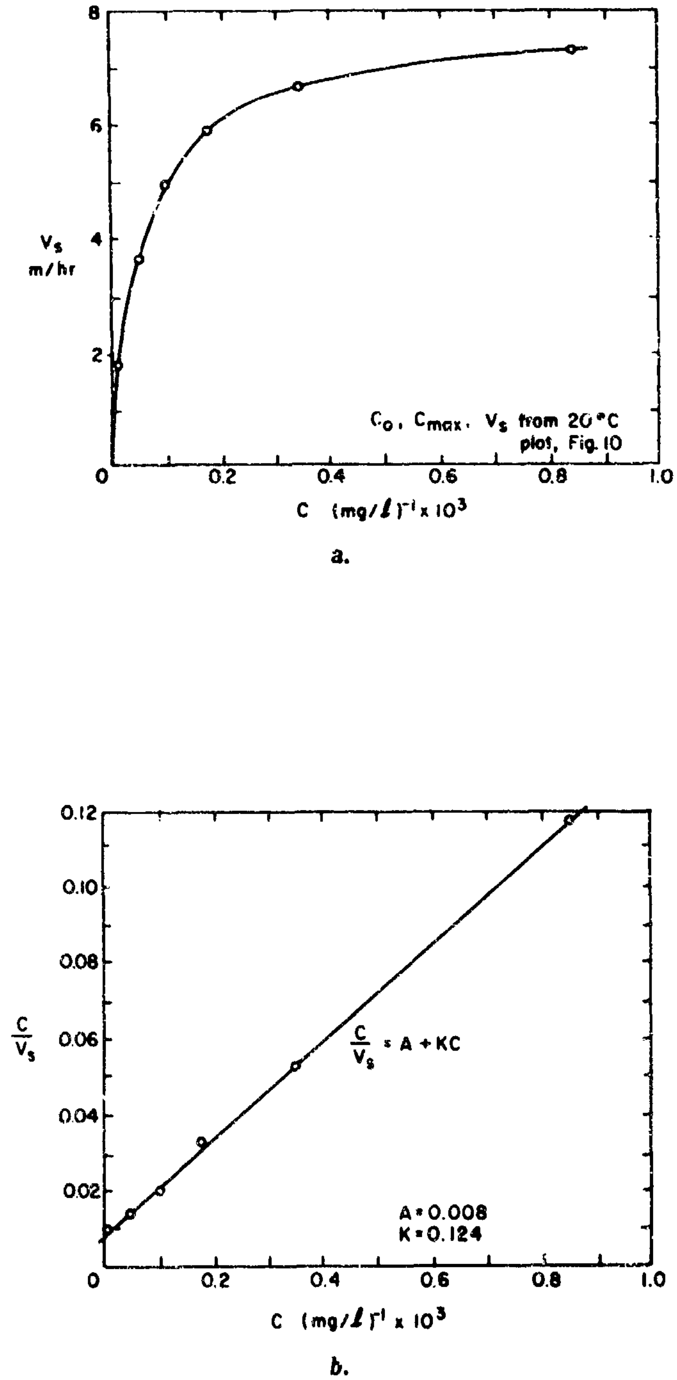


Figure 11. Determination of constants.

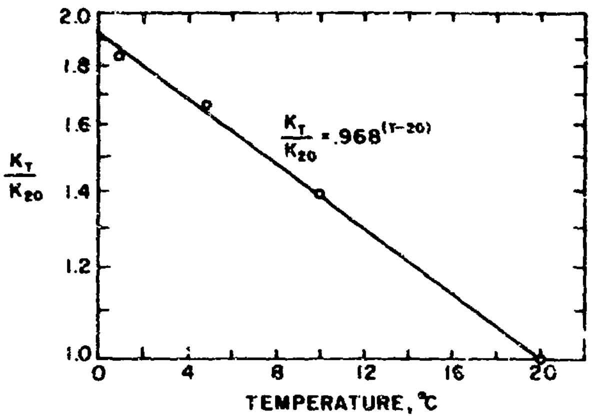


Figure 12. K_T/K_{20} vs temperature.

Table IV. Parameters A and K vs temperature.

Temperature °C	A	K_T	K_T/K_{20}
20	0.008	0.124	1.00
10	0.008	0.172	1.39
5	0.008	0.208	1.68
1	0.008	0.228	1.84

In eq 10, as C approaches infinity (which it will tend to do as the initial concentration C_0 becomes very small) the factor A becomes insignificant and the settling velocity approaches a constant value:

$$\lim_{C \to \infty} V_s = V_{ult} = \frac{1}{K_T} . \tag{12}$$

This apparent ultimate settling velocity is interpreted to represent the free, unhindered settling velocity when the initial concentration is very low. Under these conditions the ultimate settling velocities might be expected to conform approximately to the viscosity-velocity relationship as indicated by Stokes' law. This comparison is made in Figure 13. As shown, the values predicted by eq 11 are slightly lower than the viscosity ratios controlling Stokes' law settling. The correspondence is believed close enough to provide supporting evidence for eq 11 and the interpretation indicated by eq 12.

Definition of the factor A in eq 10 is not possible with just the data available from this study. It was analytically shown that A was independent of temperature and it may be seen that, when $A = 0$, the settling velocity is independent of concentration and is equal to its ultimate value. Since the settling velocity can approach this value only in the narrow range described by Stokes' law, it seems that A could be equal to zero only when the particle characteristics in the system

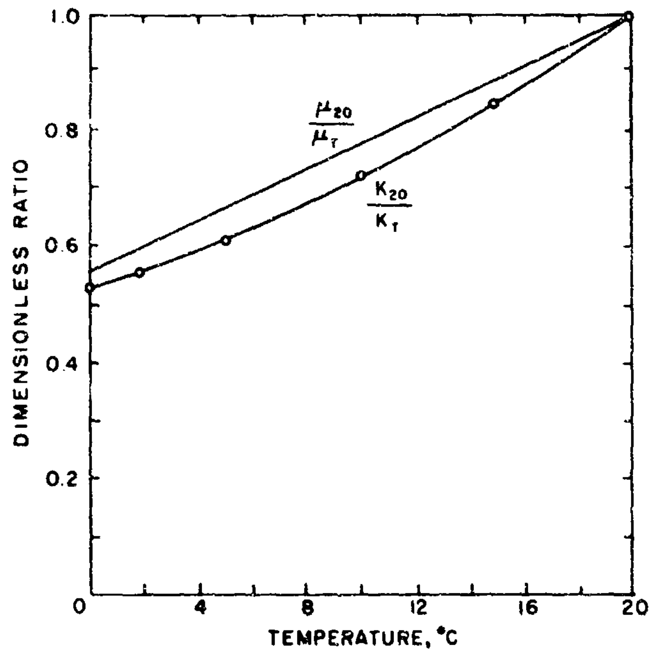


Figure 13. K and viscosity vs temperature.

were such that free, unhindered Stokes' law settling could occur. This would imply heavy, nonflocculent particles, so A might be expressed in terms of some other parameter that influences particle development in the system.

Application of derived equations

In order to test the general validity of eq 10 and to have an additional basis for the evaluation of the factor A, the same analysis was applied to the data extracted from Dick and Ewing's (1967) article, summarized in Table III. As shown in Figure 14 it was possible to produce a reasonably close fit for each of the three data sets. It was not, however, possible to apply any of the specific factors derived from the sludge studied in this investigation. Although it was necessary to determine a new C_{max}, A, and K for each set, it was still possible to describe the data with eq 10. The factors derived for these three sludges are compared in Table V with the values produced from the CRREL treatment unit.

In view of the previous discussion regarding the influence of operational and biokinetic parameters, it is not surprising that a separate analytical treatment was required for each of the sludges considered. The CRREL unit, as discussed previously, was an underloaded extended aeration system. Dick and Ewing (1967) describe their municipal plant sources as follows:

> "Plant A uses variations of the Kraus and contact stabilization modifications to the conventional activated sludge process. The retention times are somewhat less than 2 hours in the contact tanks and about 5 hours in the stabilization tanks. Plant B has the flow pattern of a conventional activated sludge unit but has an exceptionally light load. Retention time in the aeration tank is about 16 hours. Plant C is heavily loaded. An industrial carbohydrate waste accounts for more than half the organic material treated. It is a contact stabilization plant with 2 hours of contact and 5 hours of stabilization."*

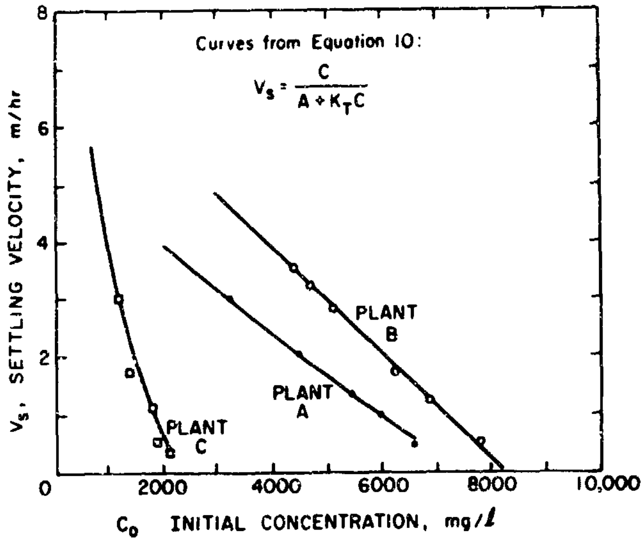


Figure 14. Zone velocity vs concentration, computed for data of Dick and Ewing (1967) (Table III).

Table V. Comparison of eq 10 constants.

Data source	C_{max}	A	K_{20}
This study	6667	0.008	0.124
Dick and Ewing (1967):			
Plant A	7500	0.031	0.170
Plant B	8350	0.017	0.130
Plant C	2250	0.110	0.100

It is obvious that of these three Plant B is operationally the most similar to the CRREL unit and, as shown in Table V, the A and K values for these two show the closest correspondence.

In attempting to determine the functional dependence of the factor A, it was noted that a correlation was possible between this factor and the organic loading on a particular system, as shown in Figure 15. The familiar shape of this curve suggested the form:

$$A = A_{ult} \, (1 - e^{-kF}). \tag{13}$$

Analysis of these data using the Thomas slope method, c... ed with successive trial and error repetitions to improve fit, produced: A_{ult} 0.115 and $k = 2.31$, which reduce eq 13 to:

$$A = 0.115 \, (1 - 0.1^{F}) \tag{14}$$

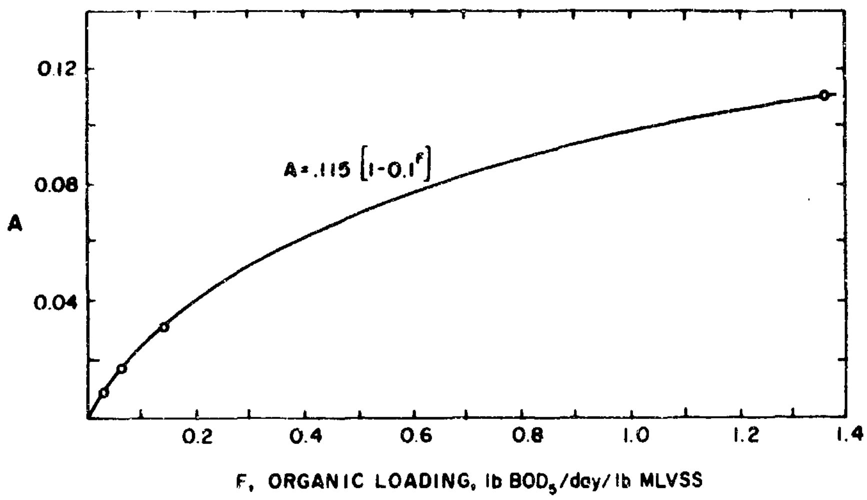


Figure 15. Factor A vs organic loading, data from Table V.

where:

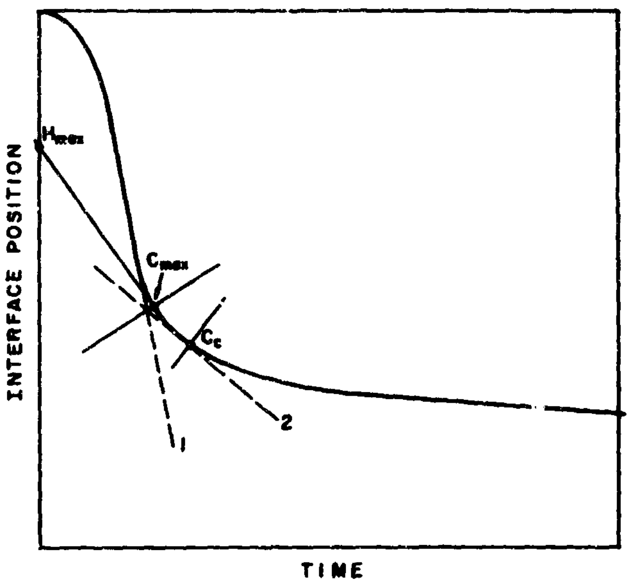
F = organic loading on system in pounds of BOD_5/day per pound of MLVSS.

Use of the organic loading as an "indicator" parameter would seem rational since the loading level will most certainly determine the biokinetic equilibrium in the system and therefore influence sludge settling characteristics. It is termed an indicator parameter because the A is believed to be more directly dependent on particle characteristics. Equation 14 would then apply only to activated sludge. For other inorganic suspensions (sand, silt, clay, etc.) the factor A might still be expected to exhibit a range of values as the particle approaches the ideal spheres assumed by Stokes' law. In these cases it may be possible to develop a direct identity between A and some particle characteristic.

Organic loading is apparently a suitable indicator for activated sludge as demonstrated on Figure 15. However, further verification in the mid-range of organic loadings shown (0.2-1.0) is necessary. Some support can be found in the work of Ford and Eckenfelder (1967), who reported on settling characteristics of sludges produced in bench scale units at various loadings. For the portion of their study based on domestic waste, as the organic loading increased from 0.15 to 0.9 lb BOD_5/day per pound of solids, the settling velocity decreased by a factor of 3 (16 ft/hr to 5 ft/hr). For the same loading range of Figure 15, the A value increases by a factor of 3, which, if other parameters in eq 10 remained constant, would produce the same change in settling velocity observed by Ford and Eckenfelder.

Design applications

Evaluation of the K_T and the C_{max} parameters in eq 10, in terms of identifiable process parameters, would permit use of the method as a general design technique. Further efforts in this direction will be made in the future. However, as shown in Figure 16, it may be possible to use the method at its present stage of development as a design tool with a minimum of laboratory testing. If, as suggested, C_{max} represents the concentration at the onset of transition settling, it should be possible to identify this point with the same graphical techniques suggested by Talmage and Fitch (1955) for C_c (Fig 3). Observation of settlement at one concentration will then provide a basis for graphical identity of V_s and C_{max}. Since A can be determined from the organic loading, it will then be possible to solve eq 10 for K_T. With these values identified, the



A. Obtain sample and run test to produce curve.

B. Analysis:

1. Construct tangent 1 to initial portion; determine V_s
2. Fix C_c point by method of Talmage and Fitch or assume 30-min settling position $\approx C_c$.
3. Construct tangent through C_c (2); bisect angle formed by this tangent and V_s tangent. Point of intersection of bisector with curve is C_{max}.
4. Construct tangent to C_{max}; extend to ordinate; determine H_{max}. Solve: $C_0 H_0 = C_{max} H_{max}$.
5. Knowing organic loading, solve: $A = .115\,[1 - 0.1^F]$.
6. Knowing, A, V_s, C_{max}, solve: $V_s = C/A + K_T C$ for K_T.
7. Can then solve $V_s = C/A + K_T C$ for any other condition.

Figure 16. Design application of settlement equation.

basic equation can then be used to solve for a settling velocity at any other concentration or temperature. Some additional laboratory testing is then suggested for either verification or refinement of the values.

In a situation where it becomes necessary to test a wide range of concentrations to confirm C_{max}, A, and K, the value of the equation is somewhat reduced since the range of settling velocities required for design purposes will be directly available from experimental observations. However, even in this case, the equation is believed to have significant value for arctic and subarctic applications since it describes the temperature dependency of the process. As shown in Figure 17, it produces a gradual transition from one limiting condition to the other (eq 6 and 7). This gradual transition would seem to offer a more rational basis for design as compared to some arbitrary choice of temperature influences.

The eq 10 curve would approach the limiting concentration value asymptotically. Since Tesařík's equation is considered to be a valid upper limit, the plot for eq 10 is terminated at that point.

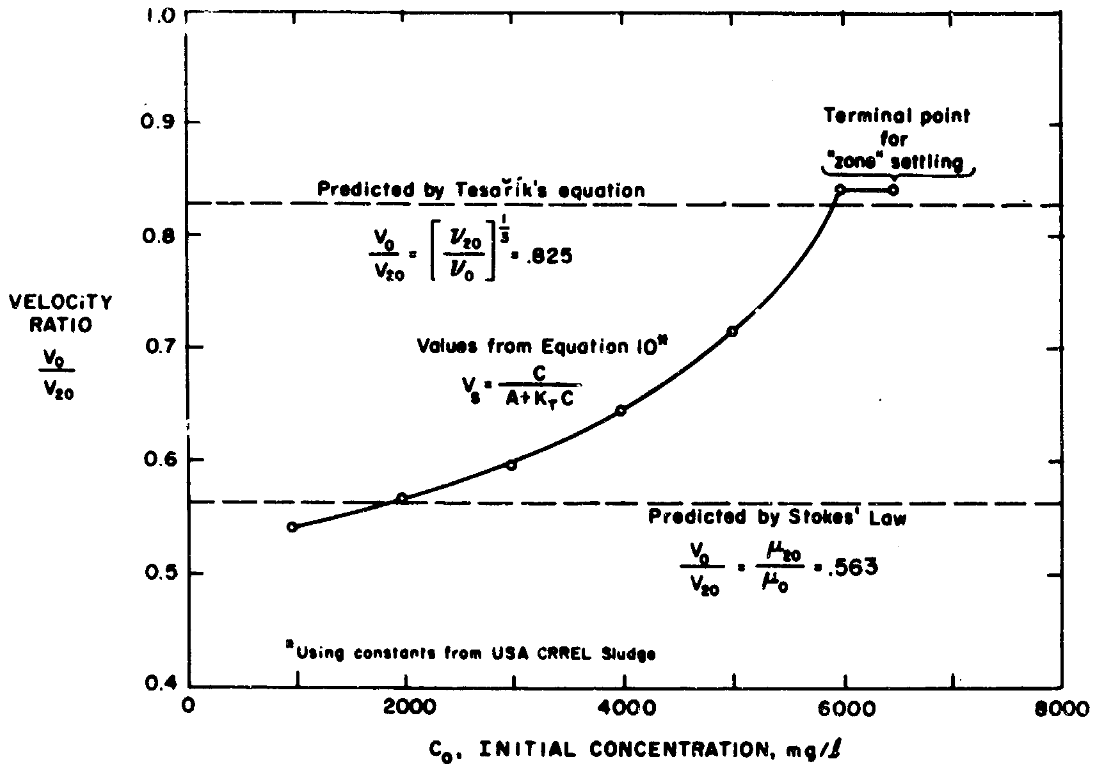


Figure 17. Velocity ratio 0°C/20°C vs concentration.

Flocculation and initial time lag

The initial time lag observed prior to the onset of zone settling (Fig. 5-7) is described by Eckenfelder and O'Connor (1961) and others as being caused by initial flocculation in the system. For the samples studied in this investigation, other mechanisms seemed to offer an alternate and generally applicable explanation. If, as suggested by Dick and Ewing (1967), a structure exists in the activated sludge suspensions, there must be a load gradient from top to bottom. Development of this gradient in the transition stage should be time dependent since, as the voids are reduced, the buoyant forces on the particles are reduced, and there is more direct contact and greater load transfer. At some point in time the load will exceed the carrying capacity of the bottom sludge structure and collapse will occur. Coupled with this collapse is the requirement for the expulsion of water in the voids by successive displacements to the clarified zone above the interface. The initial time lag is therefore suggested to be caused by the time required for structural collapse at the bottom but is more strongly dependent on the time required for void channels to the surface to become available. Once these escape channels are developed, zone settling begins and continues until the interface encounters the transition layer. The net effect initially would be similar to flocculation since the hydraulic forces opening the channels would tend to agglomerate the adjacent particles.

If classical flocculation were in fact occurring, something similar should have been observed when the dilute suspensions were examined. No evidence of flocculation during settling was visually observed in any of the low concentration series. A single test was run with a 2000-mg/l concentration in a 4-ft-tall settling tube with side sampling ports. Observations were made of suspended solids concentration with depth and time and the analysis indicated that the suspension did not display any flocculent characteristics.

Describing the initial process in terms of opening void channels provides insight into the viscosity dependence of settling. At low concentrations, escape paths are abundant so turbulence and drag are low and viscosity influences high. As the concentration increases, the level of turbulence in the system increases as the escape paths become fewer and more tortuous and the forces promoting collapse become higher. These factors would have a tendency to produce an apparent increase in Reynolds number and a corresponding decrease in temperature influence.

Stirring the bottom sludge as suggested by Dick and Ewing (1967) to accelerate collapse and enhance settling would be of maximum benefit in those cases, fortunately a majority, where sufficient escape channels for the displacement of water can be developed. Some type of rotating mechanism that could simultaneously collapse sludge structure and provide partial dewatering would have obvious benefits.

As shown in Figure 8, this initial time lag occurred in both the test cylinder and the aeration tank. A similar phenomenon might therefore be expected to occur as sludge enters a typical horizontal flow basin. In this context there are also horizontal forces in the system to consider and it seems possible that during this initial lag some of the finer fractions might escape the upper layer of the main sludge mass and stay in suspension. These isolated particles are then subject to strong viscosity influences and might not be removed in a low temperature basin. Some form of upflow clarifier would seem best suited for arctic and subarctic applications. All of the particles would enter below the sludge blanket and have less chance for escape. Since these units operate with relatively high sludge concentrations, the temperature influence, as predicted by the equations developed in this study, should be negligible. It is anticipated that the recently developed tube settling devices (Hansen *et al.*, 1967) should function in a similar manner and provide comparable benefits.

Compression observations and settleability test

Since only six tests were observed into the compression stage, there are not sufficient data to support an analytical treatment. Comparison of the results shown in Table II does give some indication that the rate of collapse, or compression velocity, is independent of temperature. This lends some support to the velocity-concentration-temperature relationships developed earlier and might be of significance in cold regions design of thickening operations.

Some variation of the 30-min settleability test has become a basic and quite often the only operational test for the smaller "packaged" units. Neither Standard Methods (APHA, 1965) nor the original source reference (Mohlman, 1934) offers any temperature control requirement for this test. As shown in Table I this value changes with test temperature. If system operation at low temperature is considered, the difference in temperature between *in-situ* fluid and test area may be significant. Depending on concentration, this may in turn have a significant effect on operational decisions. To minimize these problems it is suggested that the test be run as soon as possible after sampling and at the same fluid temperature observed in the system.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. An equation for zone settling velocity of activated sludge, based on experimental data, has been developed in this study. This equation:

$$V_s = \frac{C}{A + K_T C} \qquad (10)$$

describes the variation in settling velocity as controlled by concentration, fluid temperature and organic loading on the system. This equation provides a rational basis for the assessment of temperature influences in cold regions designs.

2. The influence of temperature on settling velocity decreases as the concentration increases. This influence ranges from full viscosity effects at very low concentrations to negligible effects at very high concentrations. This tends to make a unit designed for operation at higher concentrations theoretically more efficient since it can operate at maximum capacity continuously, while low concentration systems by necessity have excess capacity at higher temperatures. This factor, plus the capability for greater retention of the smaller particles, tends to favor upflow sludge blanket clarifiers for cold regions applications.

3. Visual observations made during this study tend to support the theory that activated sludge suspensions demonstrate structural form. It is suggested that the controlling mechanism may be structural collapse or consolidation at the bottom and concurrent expulsion of water.

4. From the limited data produced it is tentatively concluded that the compression, or thickening, of sludge is independent of fluid temperature.

Recommendations

1. It has been suggested that low temperatures by producing larger and heavier particles may enhance sludge floc development. It is recommended that this study be repeated with sludge produced at higher temperatures to evaluate this point.

2. The settling behavior of activated sludge from four different sources has been adequately described with the equation developed here. Further comparisons should be made as other data become available.

3. Application of these equations to design, with a minimum of laboratory effort, has been described. Further work is necessary to define equation parameters K_T and C_{max} in terms of treatment unit process variables. This is strongly recommended since successful results could lead to a generally applicable analytical design technique.

4. The equations derived here are based on the performance in 1-liter tubes. Comparative tests with 1-liter tubes and a full-scale basin indicated an approximately 20% difference in zone settling velocity. Further work is required to define the appropriate scale factors for general application.

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DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

U.S. Army Cold Regions Research
and Engineering Laboratory
Hanover, New Hampshire 03755

2a. REPORT SECURITY CLASSIFICATION

Unclassified

2b. GROUP

3. REPORT TITLE

SETTLING CHARACTERISTICS OF ACTIVATED SLUDGE AT LOW TEMPERATURES

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Reed, Sherwood C.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 1970	30	25

8a. CONTRACT OR GRANT NO.

b. PROJECT NO

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

Technical Report 203

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

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11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

Office, Chief of Engineers
Directorate of Military Construction
Office of Plans, Research and Systems

13. ABSTRACT

A series of activated sludge settling tests were observed with particle concentration and temperature as the controlled variables. Based on the experimental data, an equation defining settling velocity in terms of concentration, fluid temperature, and organic loading was developed. Although empirical in nature the equation provides a rational basis for the determination of temperature influence and should have special value for cold regions designs. It was possible to describe the results of other investigations with this equation.

14. KEY WORDS

Aerobic sewage treatment
Activated sludge settling tests
Sanitary engineering
Temperature in sanitary engineering

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